CR-137717

THEORETICAL EFFECT OF MODIFICATIONS TO THE UPPER SURFACE OF TWO NACA AIRFOILS USING SMOOTH POLYNOMIAL ADDITIONAL THICKNESS DISTRIBUTIONS WHICH EMPHASIZE LEADING EDGE PROFILE AND WHICH VARY LINEARLY AT THE TRAILING EDGE

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ABSTRACT

This report describes a series of low-speed airfoil designs based on modification to the NACA 64-206 and 64_1-212 airfoils. Designs are based on potential flow theory. The report describes one of a series of airfoil modifications carried out under Contract NAS 2-8599, Application of Multivariable Search Techniques to Optimal Wing Design in Non-Linear Flow Fields. Mr. Raymond Hicks of National Aeronautics and Space Administration's Aeronautical Division, Ames Research Center, served as contract monitor for the study.

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by Donald S. Hague and Antony W. Merz

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SUMMARY

An investigation has been conducted on the Lawrence Radiation Center, Berkeley, CDC 7600 digital computer to determine the effects of additional thickness distributions to the upper surface of the NACA 64-206 and 64_1-212 airfoils. The additional thickness distribution had the form of a continuous mathematical function which disappears at both the leading edge and the trailing edge. The function behaves as a polynomial of order ε_1 at the leading edge, and a polynomial of order ε_2 at the trailing edge. In the present study, ε_2 is a constant and ε_1 is varied over a range of practical interest. The magnitude of the additional thickness, $\bar{y}$, is a second input parameter, and the effect of varying ε_1 and $\bar{y}$ on the aerodynamic performance of the airfoil was investigated. Results were obtained at a Mach number of 0.2 with an angle-of-attack of 6° on the basic airfoils. All calculations employ the full potential flow equations for two dimensional flow. The relaxation method of Jameson is employed for solution of the potential flow equations.

As was found in earlier investigations of these airfoils, using other types of additional thickness distribution, increasing the additional thickness, $\bar{y}$, tends to increase both the lift and the adverse pitching moment coefficients. In the present investigation variations in the shape parameter, ε_1, also change the lift and moment coefficients proportionally and monotonically. For the range of coefficients examined, the lift coefficient was nearly insensitive to changes in ε_1, while the pitching moment coefficient showed stronger variations to this parameter. For both the 64-206 and 64_1-212 airfoils, however, the lift and moment

coefficients were much more sensitive to changes in $\bar{y}$ than to changes in ε_1.

Additional thickness can be made to produce significant reductions in peak pressure coefficient. This is particularly true for the 64-206 airfoil, which in its unmodified form has a very high pressure peak at the leading edge, due to the small radius of curvature at this point. For this airfoil, the present results indicate a complex dependence of the peak pressure coefficient on the parameters ε_1 and $\bar{y}$. Study of this dependence was limited due to the increases in adverse pitching moment which accompanied the decreases in peak pressure coefficient. For the limited range of parameter variations conducted, the peak pressure and lift coefficient of the 64_1-212 airfoil followed similar patterns with variations in ε_1 and $\bar{y}$. For this airfoil the peak pressure reduced monotonically with ε_1, while the lift increased monotonically with thickness, $\bar{y}$.

It should be noted that viscous effects are neglected in the present analysis. At the higher lift coefficients the effect of viscosity could be significant. Further investigations incorporating a viscous flow model are therefore desirable.

INTRODUCTION

The National Aeronautics and Space Administration and others are currently conducting a series of theoretical and experimental studies to define airfoil sections having improved performance from the aspects of lift, drag, pitching moment, or pressure distribution characteristics, references 1 and 2. Analytic investigations using airfoil surface representations based on high-order polynomials may result in impractical profiles; for example, very thin trailing edge thickness distributions or severe reflexes in the profile. The present study employs a continuous polynomial arc having two free parameters, whose characteristics are selected to avoid such problems. Previous optimization studies using multivariable search techniques, references 1, 4 and 5, generally indicate that shape changes which provide increased lift produce unfavorable changes in moment characteristics. Conversely, profile changes which improve the moment characteristics decrease the lift coefficient. With the low-order

model of the present investigation a systematic examination on the effect of profile changes can be carried out. This was accomplished and the trends previously revealed by optimization studies were confirmed.

MATHEMATICAL MODELS

Potential Flow Equation

Potential flow analysis is based on solution of the two-dimensional potential flow equation

$$(a^2-u^2)\ \phi_{xx} + (a^2-v^2)\ \phi_{yy} - 2uv\ \phi_{xy} = 0$$

where ϕ is the velocity potential, u and v are the velocity components

$$u = \phi_x,\ v = \phi_y$$

and a is the local speed of sound determined from the energy equation and the stagnation speed of sound

$$a^2 = a_o^2 - \left(\frac{\gamma - 1}{2}\right) (u^2 + v^2)$$

Solutions are obtained by Jameson's finite difference scheme, reference 6.

AIRFOIL PROFILE REPRESENTATION

Basic Airfoil

Ordinates for the basic NACA 64-206 and 64_1-212 airfoils were approximated by four cubic chain polynomials in the manner of Hicks

$$y_j = a_{o_j} F_j + a_{1_j} x + a_{2_j} x^2 + a_{3_j} x^3;\ j = 1,2,3,4$$

Coefficients in the four polynomial arcs are selected on the following basis:

j = 1 - Arc represents forward portion of upper surface

$$F_1 = \sqrt{x}$$

j = 2 - Arc represents aft portion of upper surface

$$F_2 = 1$$

j = 3 - Arc represents forward portion of lower surface

$$F_3 = \sqrt{x}$$

$\underline{j = 4}$ - Arc represents aft portion

$$F_4 = 1$$

The coefficients a_{i_j} are determined by introducing four boundary conditions on the airfoil profile in each of the four airfoil arcs. Crout's method for triangularization and back substitution is used to solve the resulting system of linear equations. Note that if four points are specified on the aft portion (i = 2 or 4), a discontinuity in slope occurs where the polynomials join. This produces a small ripple in the pressure distribution at the juncture point. However, since the juncture occurs at a region of small slope (x = .5) the effect is not significant.

Computer-generated plots of the NACA 64-206 and 64_1-212 airfoils, together with the associated pressure distributions predicted by potential flow theory, are shown in Figure 1. Table I lists the polynomial coefficients, a_{i_j}, which are used for the basic airfoil representations.

Additional Thickness

The upper surface of the basic airfoil is modified by addition of the thickness-distribution function,

$$\Delta y(x) = Ax^{\varepsilon_1} (1 - x)^{\varepsilon_2}$$

where $\varepsilon_2 = 1$, for the present study. It is shown in Appendix A that the magnitude parameter, A, can be expressed in terms of the maximum thickness, $\bar{y}$, by the equation,

$$A = \bar{y}\left[\frac{(1 + \varepsilon_1)}{\varepsilon_1^{\varepsilon_1}}\right]^{1 + \varepsilon_1}$$

Representative functions $\Delta y(x)$ are shown in Figure 2, for ε_1 = .25, .50 and .75. Notice that the slope of the additional thickness distribution is infinite at the leading edge (x = 0) and is finite and positive at the trailing edge (x = 1). Notice also that the leading edge shape is very sensitive to this exponent, and that values of ε_1 less than .25 produce a very blunt nose on the airfoil. The chordwise location of the point of maximum thickness is shown in Figure 2(d) as a function of the shaping parameter ε_1.

TABLE I. COEFFICIENTS FOR AIRFOIL REPRESENTATIONS

64-206 Airfoil

j		a_0	a_1	a_2	a_3
1	Upper Surface, Forward	.07784	.00098	-.01209	-.10986
2	Upper Surface, Aft	.02453	.10936	-.18959	.05569
3	Lower Surface, Forward	-.06050	.05728	.08033	.14000
4	Lower Surface, Aft	-.01026	-.09394	.21987	-.11567

64_1-212 Airfoil

j		a_0	a_1	a_2	a_3
1	Upper Surface, Forward	.14641	-.01941	.00039	-.22475
2	Upper Surface, Aft	.03227	.27010	-.50591	.20715
3	Lower Surface, Forward	-.12650	.07374	-.09721	.26487
4	Lower Surface, Aft	-.01021	-.29552	.60784	-.30212

OPTIMIZATION STUDIES

In previous airfoil optimization studies, (references 4 and 5), the modifications to the upper surface took the form of a pair of quadratic arcs, which were cotangential at the point $\bar{x}$, $\bar{y}$. These parameters are respectively the chordwise location of the maximum addition thickness and the value of this thickness. Both lift coefficient and moment coefficient were considered as performance indices in this development. The present study is also concerned with a two variable optimization problem using the leading edge thickness distribution exponent, ε_1, and the magnitude of additional thickness, $\bar{y}$.

Lift Coefficient Maximization

In general, maximization of lift coefficient has the form

$$\phi = \text{Max}\left[C_L\right]$$

where

$$C_L = \oint \Delta p(x)\,dx$$

and the integration is around the airfoil contour. The airfoil contour in the present study and those of references 4 and 5 are completely described in terms of two parameters, α_1 and α_2. For the present airfoils

$$\phi = \text{Max}\left[C_L\right] = \text{Max}\left[C_L(\varepsilon_1,\bar{y})\right] \equiv \text{Max}\left[C_L(\alpha_1,\alpha_2)\right]$$

where

$$\alpha_{1_L} \le \alpha_1 \le \alpha_{1_H}$$

$$\alpha_{2_L} \le \alpha_2 \le \alpha_{2_H}$$

This two variable optimization problem can be solved by use of multivariable search techniques, for example, a combination of directed random-ray and pattern searches, references 3 and 7.

Examples illustrating this type of search procedure have previously been presented in references 4 and 5. However, the low dimensionality of the present problem (two parameters) permits the solution of optimization problems by inspection of graphical results. This procedure is employed in the present report. Other optimization problems of interest are described below.

Moment Coefficient Minimization

Minimization of the moment coefficient has form

$$\phi = \text{Min}\left[C_M\right] = \text{Min}\left[C_M(\varepsilon_1,\bar{y})\right] \equiv \text{Min}\left[C_M(\alpha_1,\alpha_2)\right]$$

where

$$C_M = \oint (x - 1/4)\ \Delta p(x)dx$$

In previous studies moment minimization resulted in a solution directly opposed to lift maximization. The position of maximum thickness moved forward and the amount of additional thickness was minimized. Thus in those studies the basic airfoil had less adverse moment than any airfoil generated by addition of the specified thickness to the upper surface of the airfoil.

Other Optimization Criteria

Other airfoil performance criteria can be considered, which typically involve compromises between lift, moment and peak pressure coefficients. Such modified criteria can take any of the following forms:

1. Maximize a linear combination of lift and moment:

$$\phi = \text{Max}\left[C_L - aC_M\right]$$

2. Minimize the moment at a specific value of lift:

$$\phi = \text{Min}\left[C_M\right]_{\bar{C}_L}$$

3. Minimize the peak pressure at a specific value of lift:

$$\phi = \text{Min}\left[C_{p_{max}}\right]_{\bar{C}_L}$$

In the studies reported in references 4 and 5, the parameters available for airfoil modification ($\bar{x}$ and $\bar{y}$), both were varied over a large range. This permitted a straightforward interpretation of results, such that optimal parameter pairs for a given performance criterion could be determined by inspection. As noted above, this procedure is also followed in the present study. Free variables for the present study are the parameters ε_1 and $\bar{y}$.

SYSTEMATIC AIRFOIL SHAPING

The present study is primarily concerned with a limited but systematic investigation on the effects of varying the leading edge thickness magnitude and distribution for the NACA 64-206 and 64_1-212 airfoils. The parameters $\bar{y}$ and ε_1 are varied over ranges which are sufficient to permit qualitative conclusions as to their effects on lift, moment, and peak pressure coefficients. For each pair of such parameters, a plot of the airfoil and its associated calculated pressure distribution are given in Figures 3(a) to 3(r).

The first 12 of these plots relate to modifications of the 64-206 airfoil, and the last 6 are related to modifications of the 64_1-206 airfoil. These pressure signatures differ from those of the basic airfoils (Figure 1) chiefly in the magnitude of the peak pressure at the leading edge. Increases in both ε_1 and in $\bar{y}$ tend to soften the pressure variations over the upper surface by reducing the leading edge peak and by increasing pressures over the central and trailing edge regions. In the case of the modified 64-206 airfoil high values of ε_1 ultimately reverse this trend and the strong overpressure peak reappears.

Lift and moment coefficient variation for the two airfoils are shown in Figure 4, and the effects of varying the parameter ε_1 and $\bar{y}$ are apparent. For both airfoils, the lift increases only slightly with the exponent ε_1, while the thickness $\bar{y}$ has a more pronounced influence on the lift increment. The adverse moment coefficient also rises sharply with additional thickness, while the exponent ε_1 has a more significant influence on C_M. Combined lift vs. moment results are given in Figure 5, which shows that the least adverse moment is obtained at a given $\bar{y}$, or at a given C_L, with the smallest value of ε_1. This corresponds to a relatively blunt leading edge on the airfoil.

Variations of the peak pressure with the parameters ε_1 and $\bar{y}$ are shown in Figure 6 for the two airfoils being studied. The pressure variation for both airfoils is minimized at a particular $\bar{y}$ by a specific choice of ε_1. For the 64_1-212 airfoil peak overpressure at a given lift coefficient is minimized by using the largest leading edge exponent value, ε_1. The C_L-$C_{p_{max}}$ variation is more complex for the 64-206 airfoil, however, in that the constant ε_1 loci cross each other. The envelope of these curves is given in Figure 7, and it defines the minimum peak pressure for a

given lift. The small number of data points available in this study does not permit accurate cross-plotting, so the estimated minimum pressure peak values are shown in the cross-hatched area. Despite the uncertainties in the cross-plotting procedure it is evident that the present family of airfoil designs produce lower peak overpressures for a given C_L than the airfoils previously obtained through biquadratic modifications.

Qualitative results of this parametric study are summarized in Table II. These conclusions follow directly from the results shown in Figures 4 to 7. Figure 7 also presents the minimum peak overpressures obtained with biquadratic airfoil modifications in references 4 and 5.

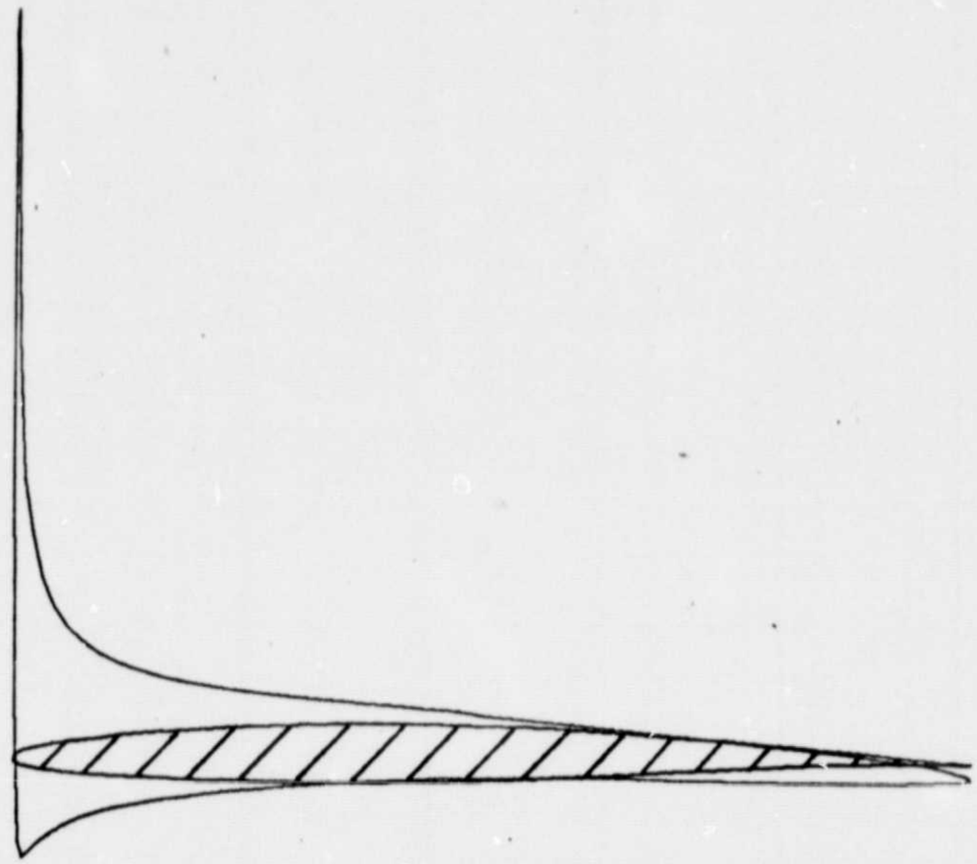
CONCLUSION

A numerical study has been completed of a class of modifications to the NACA 64-206 and 64_1-212 airfoils. Systematic changes in the upper surfaces of these airfoils were studied by independent variations in the thickness and leading edge thickness distribution exponent. The Mach number and angle-of-attack were constant during the study, and the results are summarized as follows:

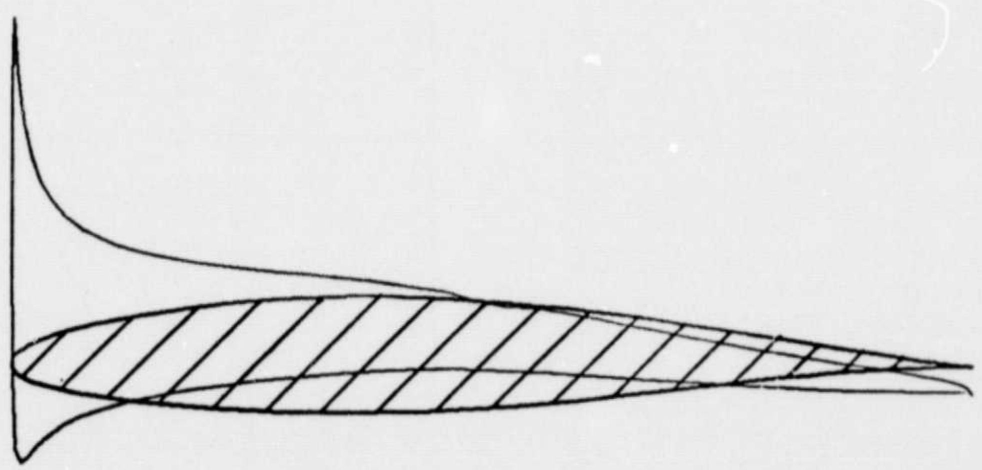
1. Pressure distribution is moderately sensitive to leading edge profile and to additional thickness.
2. Lift coefficient is nearly independent of the leading edge profile, but increases with additional thickness.
3. Adverse pitching moment increases with additional thickness and with increases in the leading edge profile exponent. All modifications to the airfoils increased this adverse moment.
4. Peak pressure for a given lift coefficient can be considerably reduced by careful selection of the leading edge additional thickness distribution exponent. Somewhat lower peak pressures at a given lift are possible using the present airfoil modifications, as compared with the "biquadratic" modifications of references 4 and 5.
5. For a given lift coefficient, adverse pitching moment is minimized by reducing the leading edge profile exponent.

TABLE II. PARAMETRIC VARIATIONS FOR OPTIMIZING VARIOUS CRITERIA

	Criterion	Exponent ε_1	Thickness $\bar{y}$	Comment
64-206 Airfoil	Max $\left[C_L\right]$	Max	Max	
	Min $\left[\lvert C_m\rvert\right]$	Min	Min	Basic airfoil is best
	Min $\left[\lvert C_m\rvert\right]_{\bar{C}_L}$	Min	$\bar{y} = \bar{y}\ (C_L)$	
	Min $\left[\lvert C_{p_{max}}\rvert\right]_{\bar{C}_L}$	$\varepsilon_1 = \varepsilon_1\ (C_L)$	$\bar{y} = \bar{y}\ (C_L)$	Insensitive to $\bar{y}$
64_1-212 Airfoil	Max $\left[C_L\right]$	Max	Max	Insensitive to ε_1
	Min $\left[\lvert C_m\rvert\right]$	Min	Min	Basic airfoil is best
	Min $\left[\lvert C_m\rvert\right]_{\bar{C}_L}$	Min	$\bar{y} = \bar{y}\ (C_L)$	
	Min $\left[\lvert C_{p_{max}}\rvert\right]_{\bar{C}_L}$	Max	$\bar{y} = \bar{y}\ (C_L)$	



(a) 64-206 Airfoil



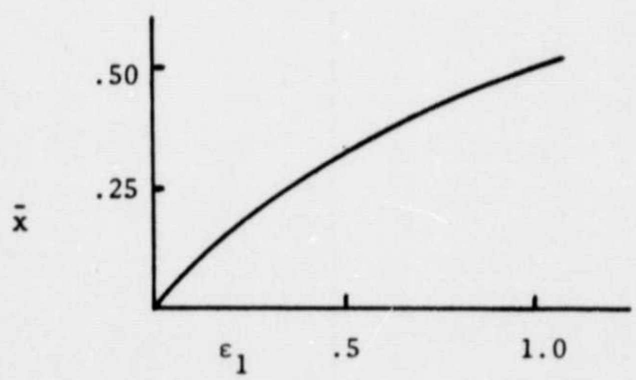
(b) 64_1-212 Airfoil

FIGURE 1. UNMODIFIED AIRFOILS AND PRESSURE DISTRIBUTIONS

(a) ε_1 = .25

(b) ε_1 = .50

(c) ε_1 = .75



(d) Chordwise Location of Maximum Thickness

FIGURE 2. UPPER SURFACE MODIFICATIONS (ε_2 = 1)

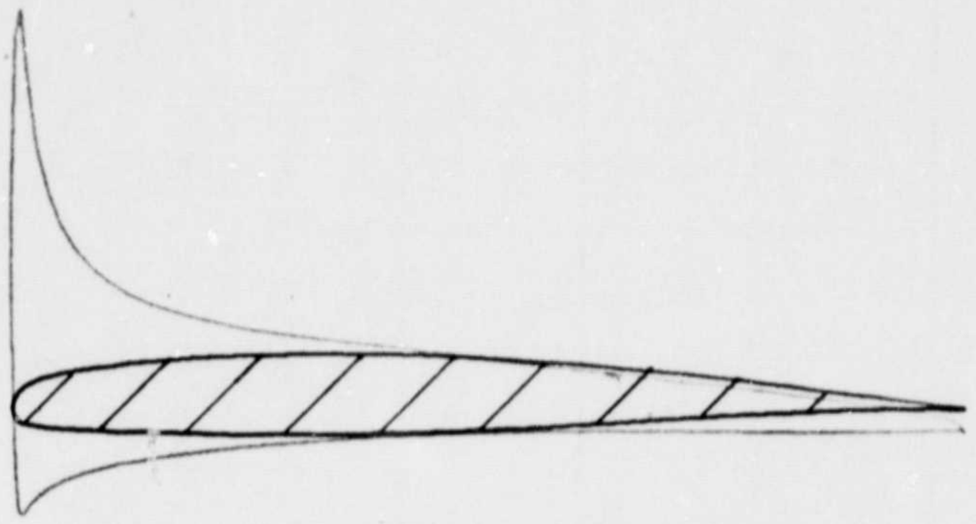


FIGURE 3(a). MODIFIED 64-206 AIRFOIL $\bar{y}$ = .03, ε_1 = .10, ε_2 = 1

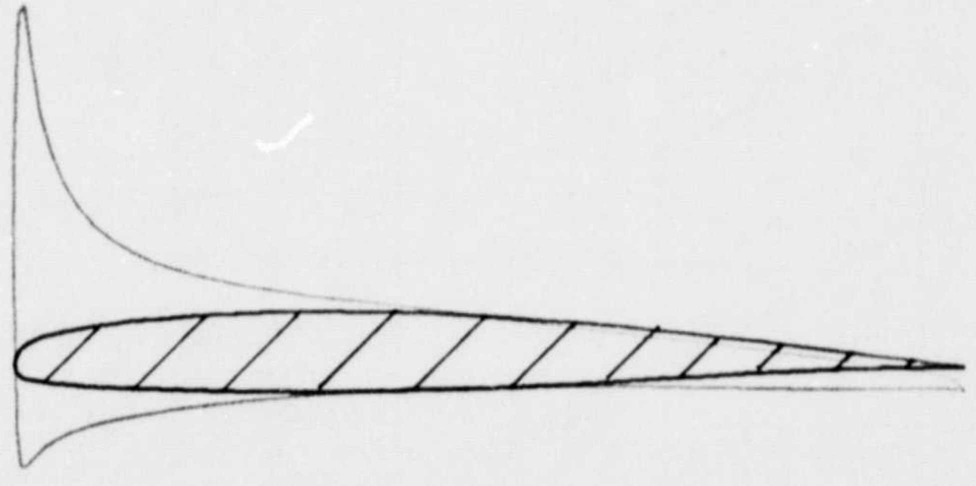


FIGURE 3(b). MODIFIED 64-206 AIRFOIL $\bar{y}$ = .03, ε_1 = .15, ε_2 = 1

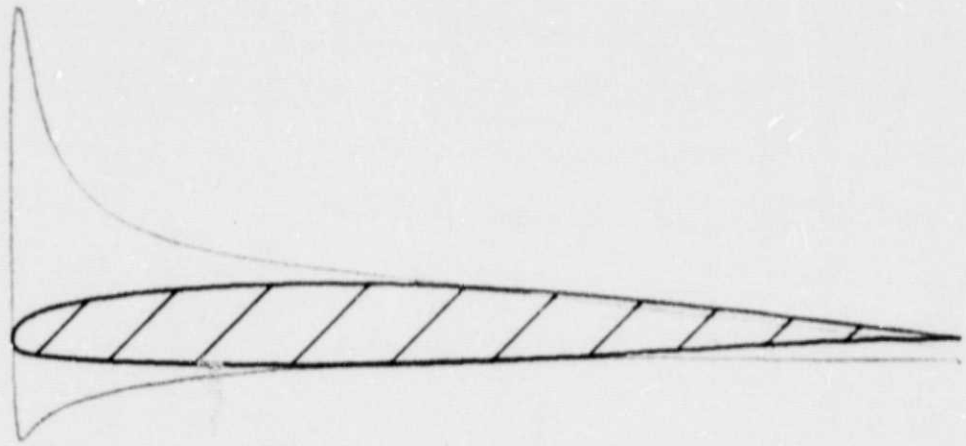


FIGURE 3(c). MODIFIED 64-206 AIRFOIL $\bar{y}$ = .03, ϵ_1 = .20, ϵ_2 = 1

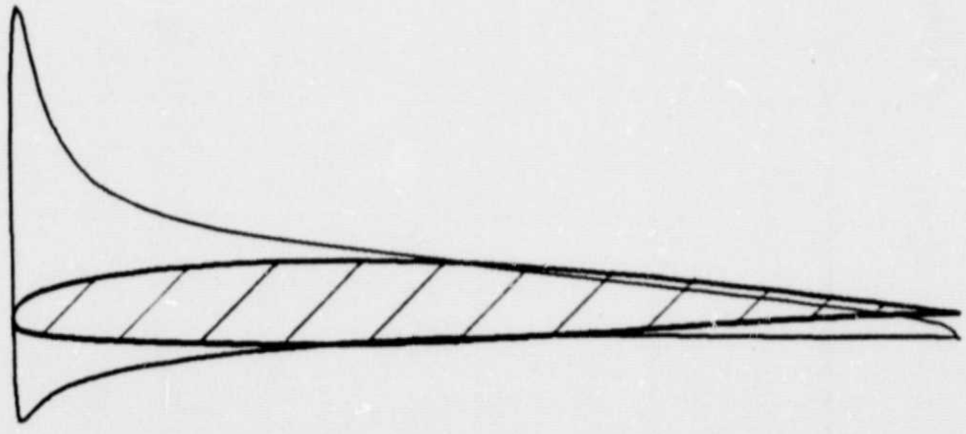


FIGURE 3(d). MODIFIED 64-206 AIRFOIL $\bar{y}$ = .03, ϵ_1 = .25, ϵ_2 = 1

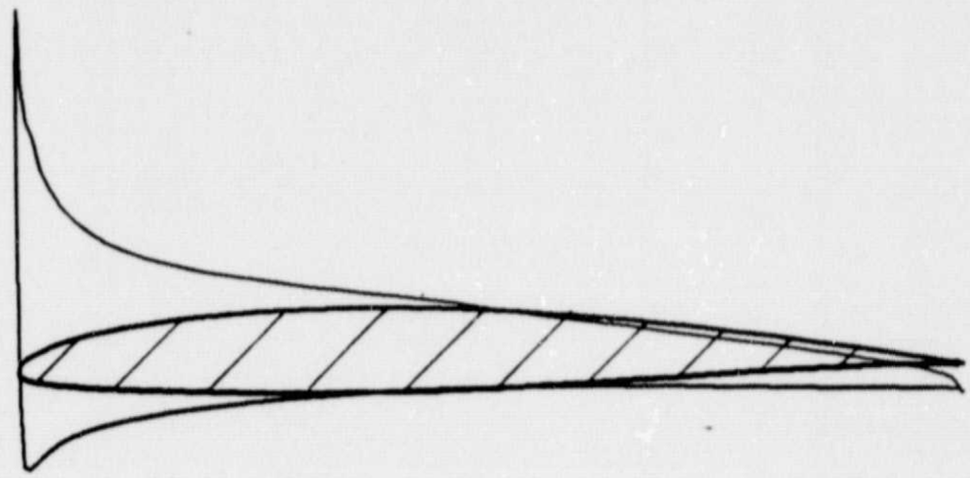


FIGURE 3(e). MODIFIED 64-206 AIRFOIL $\bar{y}$ = .03, ε_1 = .50, ε_2 = 1

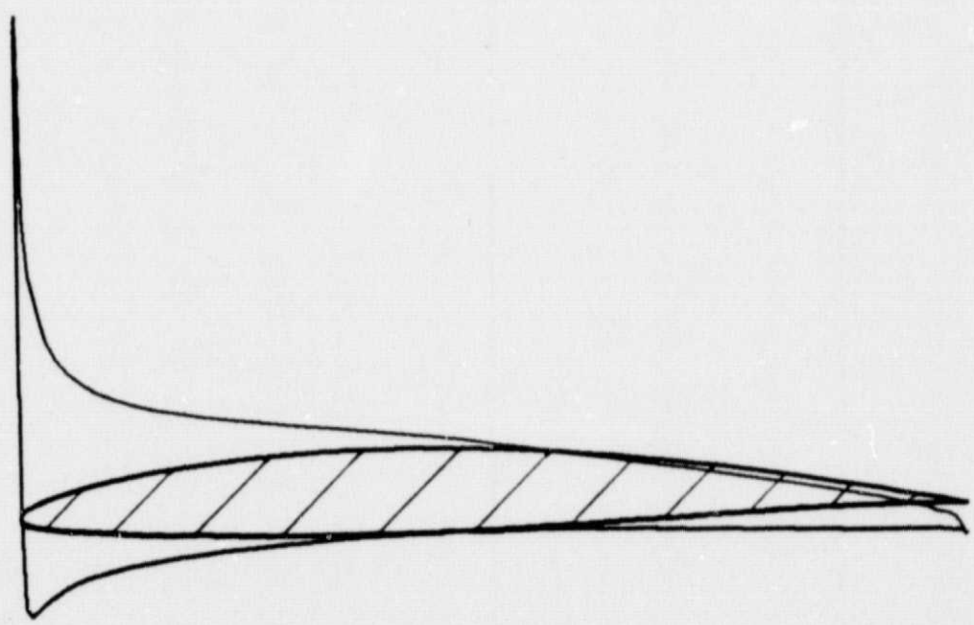


FIGURE 3(f). MODIFIED 64-206 AIRFOIL $\bar{y}$ = .03, ε_1 = .75, ε_2 = 1

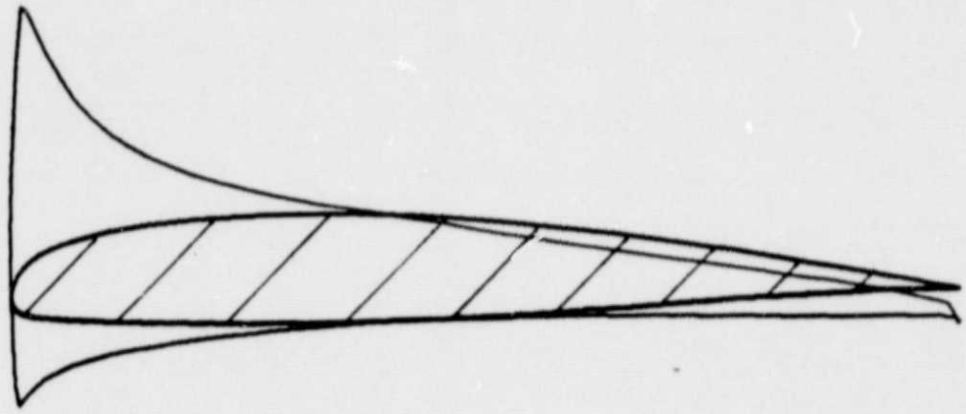


FIGURE 3(g). MODIFIED 64-206 AIRFOIL $\bar{y}$ = .06, ε_1 = .25, ε_2 = 1

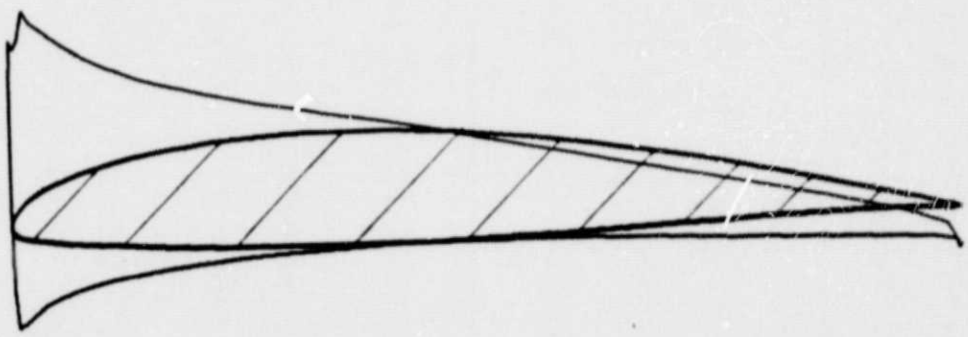


FIGURE 3(h). MODIFIED 64-206 AIRFOIL $\bar{y}$ = .06, ε_1 = .50, ε_2 = 1

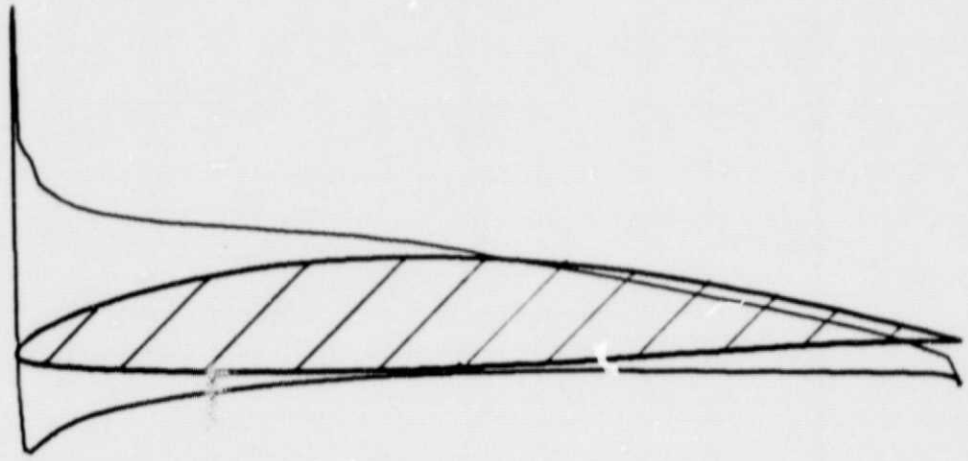


FIGURE 3(i). MODIFIED 64-206 AIRFOIL $\bar{y}$ = .06, ε_1 = .75, ε_2 = 1

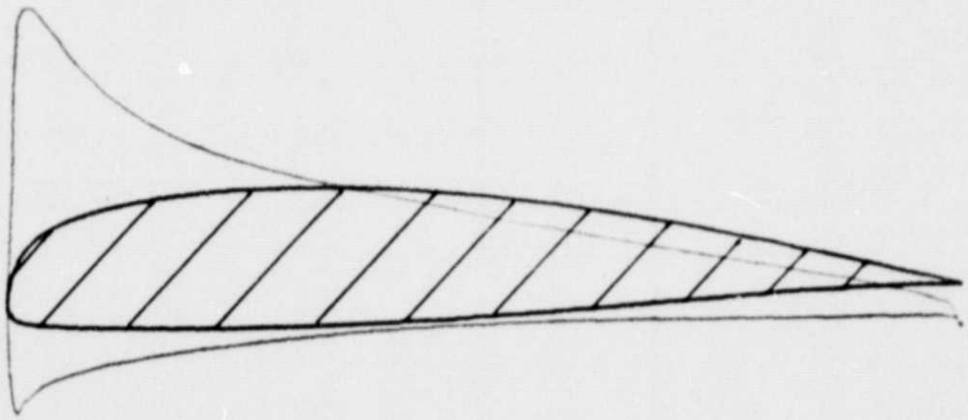


FIGURE 3(j). MODIFIED 64-206 AIRFOIL $\bar{y}$ = .09, ε_1 = .25, ε_2 = 1

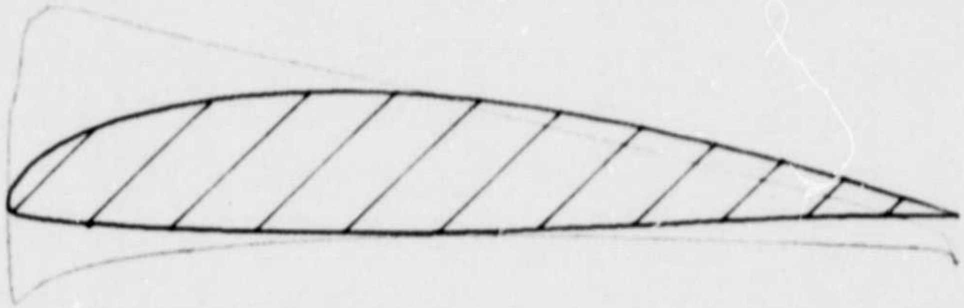


FIGURE 3(k). MODIFIED 64-206 AIRFOIL $\bar{y}$ = .09, ε_1 = .50, ε_2 = 1

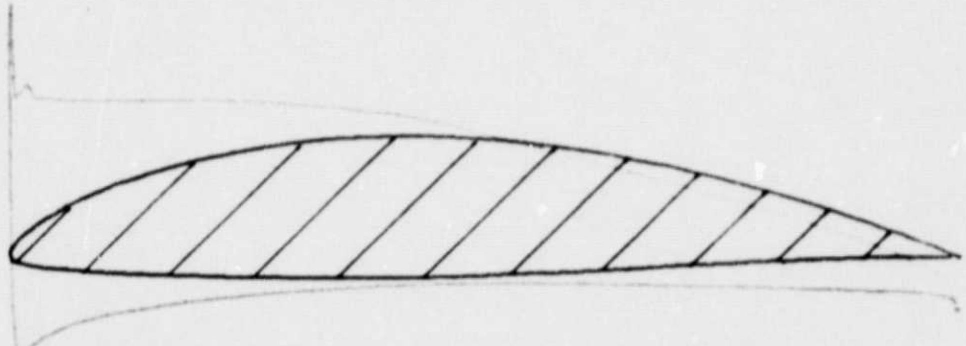


FIGURE 3(l). MODIFIED 64-206 AIRFOIL $\bar{y}$ = .09, ε_1 = .75, ε_2 = 1

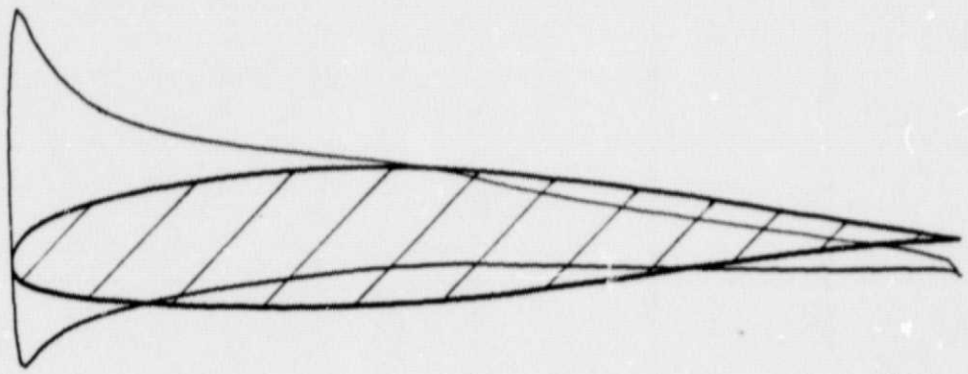


FIGURE 3(m). MODIFIED 64_1-212 AIRFOIL $\bar{y}$ = .03, ε_1 = .2, ε_2 = 1

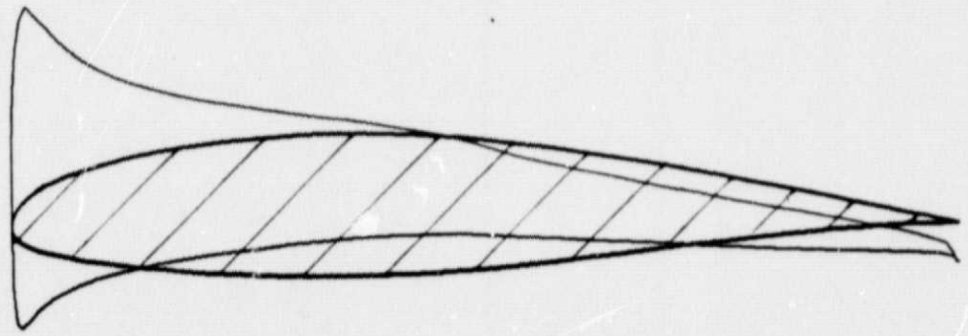


FIGURE 3(n). MODIFIED 64_1-212 AIRFOIL $\bar{y}$ = .03, ε_1 = .35, ε_2 = 1

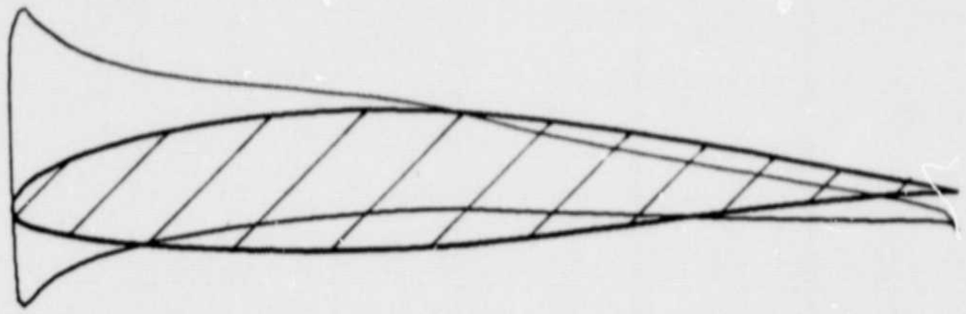


FIGURE 3(o). MODIFIED 64_1-212 AIRFOIL $\bar{y}$ = .03, ε_1 = .5, ε_2 = 1

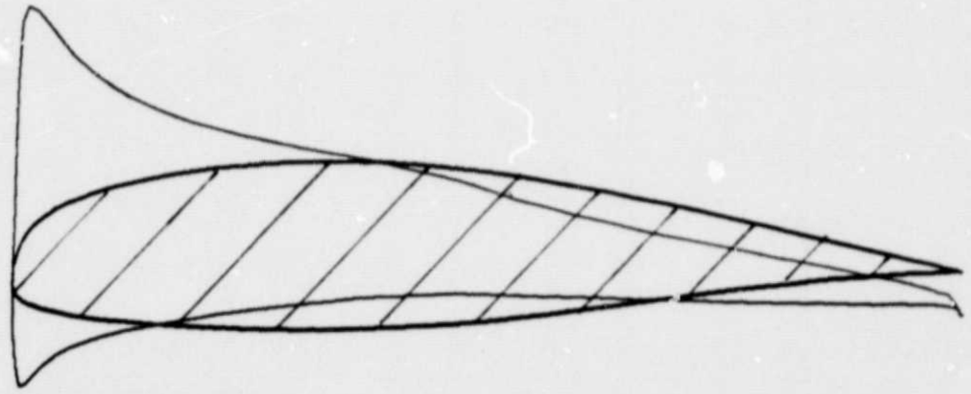


FIGURE 3(p). MODIFIED 64_1-212 $\bar{y}$ = .06, ε_1 = .2, ε_2 = 1

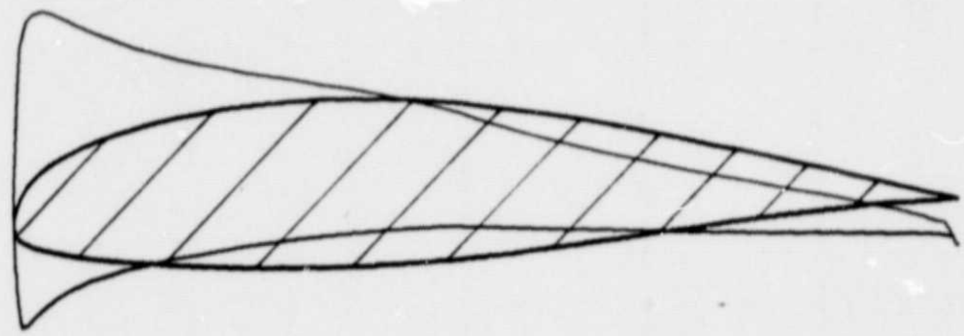


FIGURE 3(q). MODIFIED 64_1-212 $\bar{y}$ = .06, ε_1 = .35, ε_2 = 1

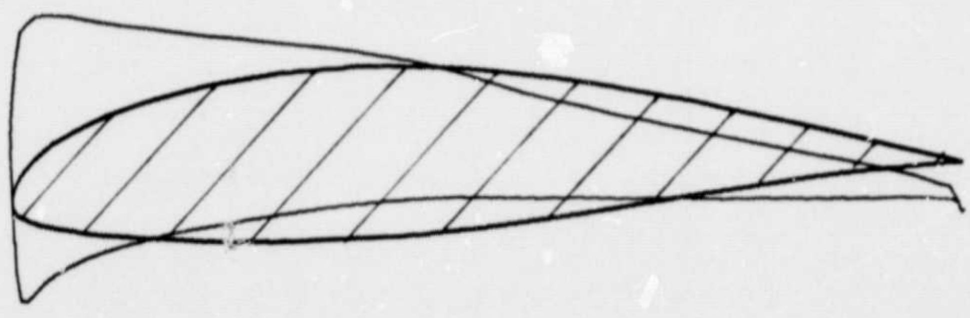
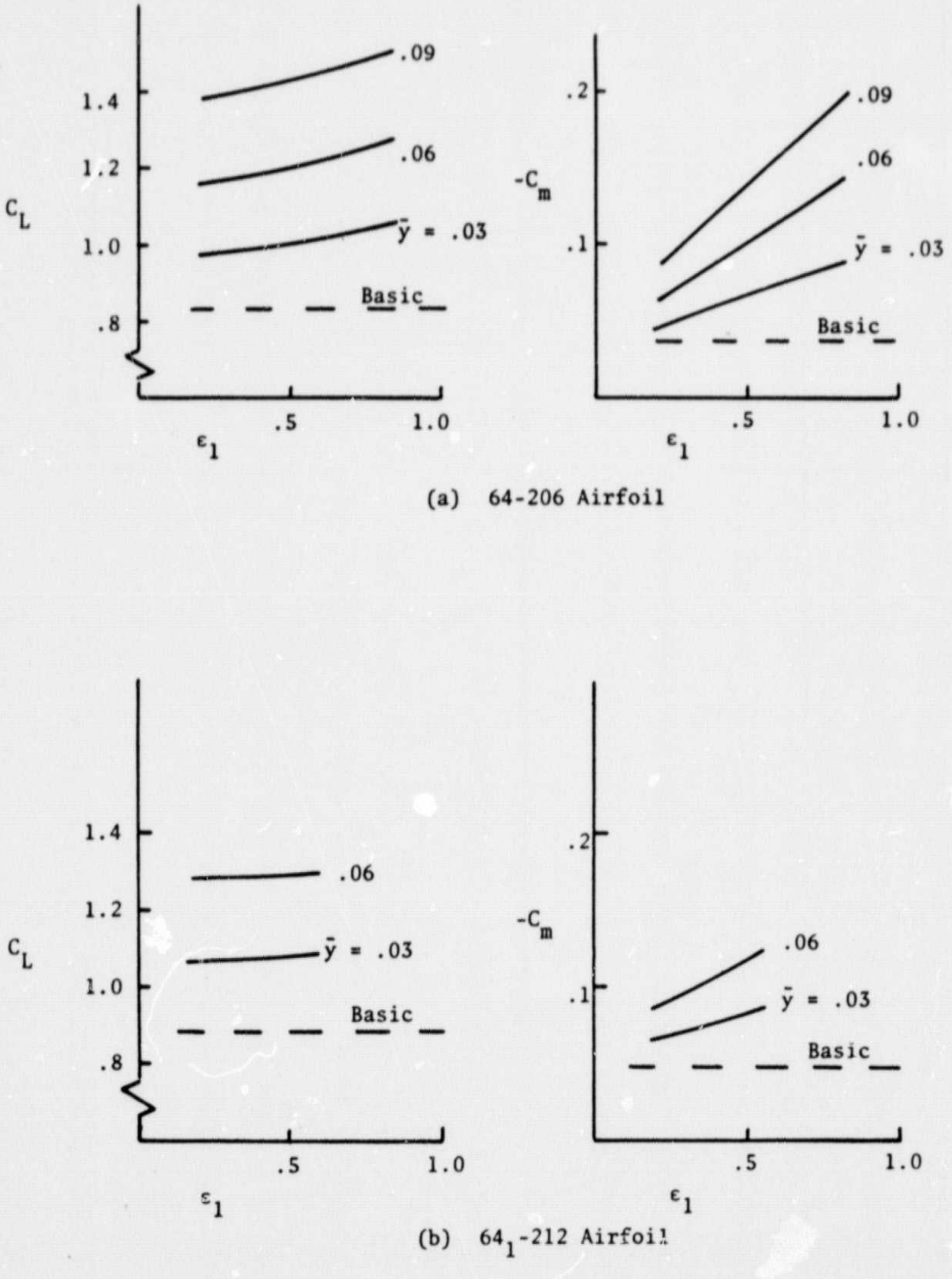


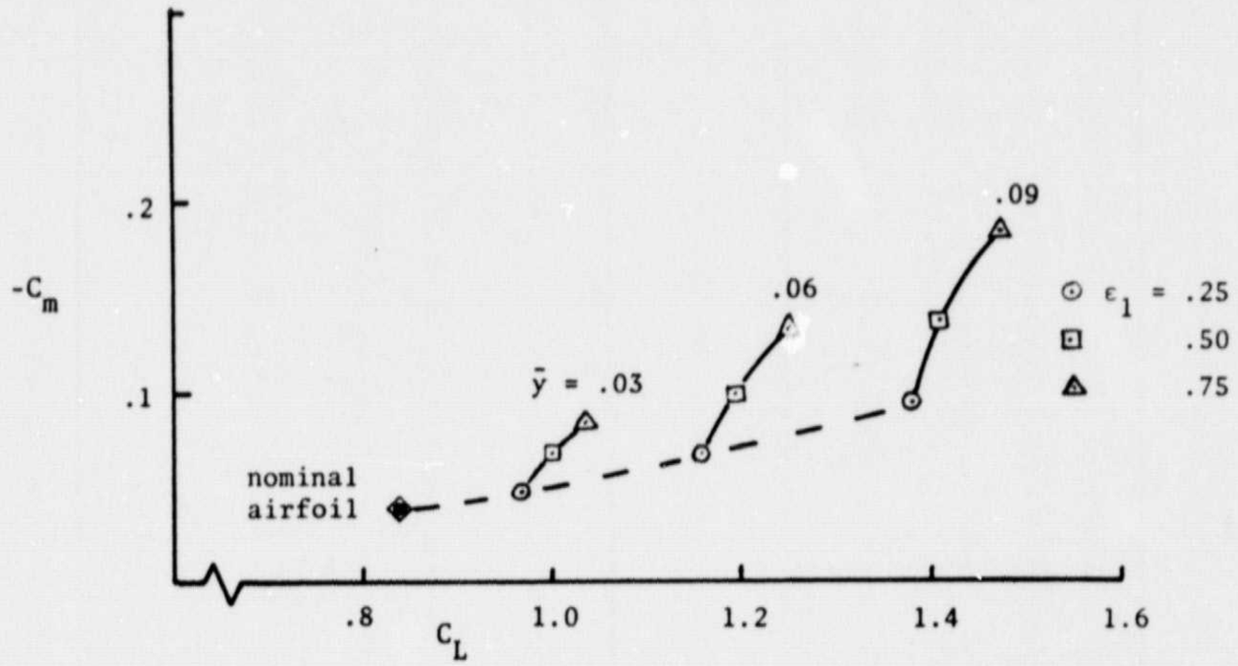
FIGURE 3(r). MODIFIED 64_1-212 $\bar{y}$ = .06, ε_1 = .5, ε_2 = 1



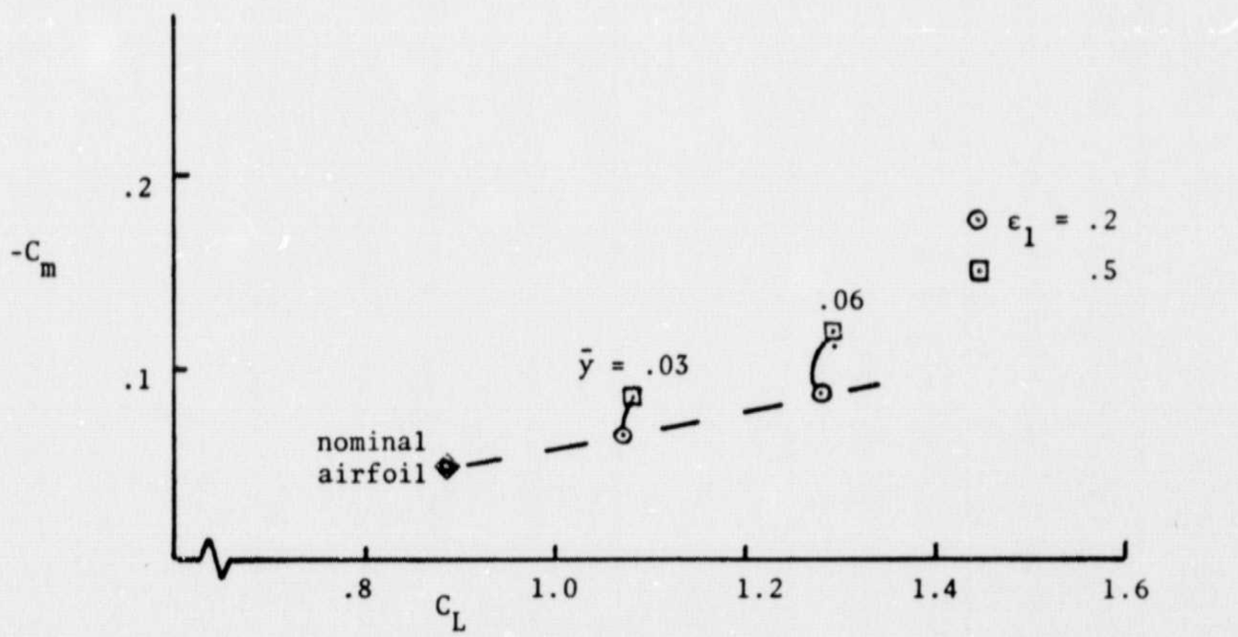
(a) 64-206 Airfoil

(b) 64_1-212 Airfoil

FIGURE 4. AERODYNAMIC COEFFICIENT VARIATIONS WITH EXPONENT ϵ_1 & THICKNESS $\bar{y}$

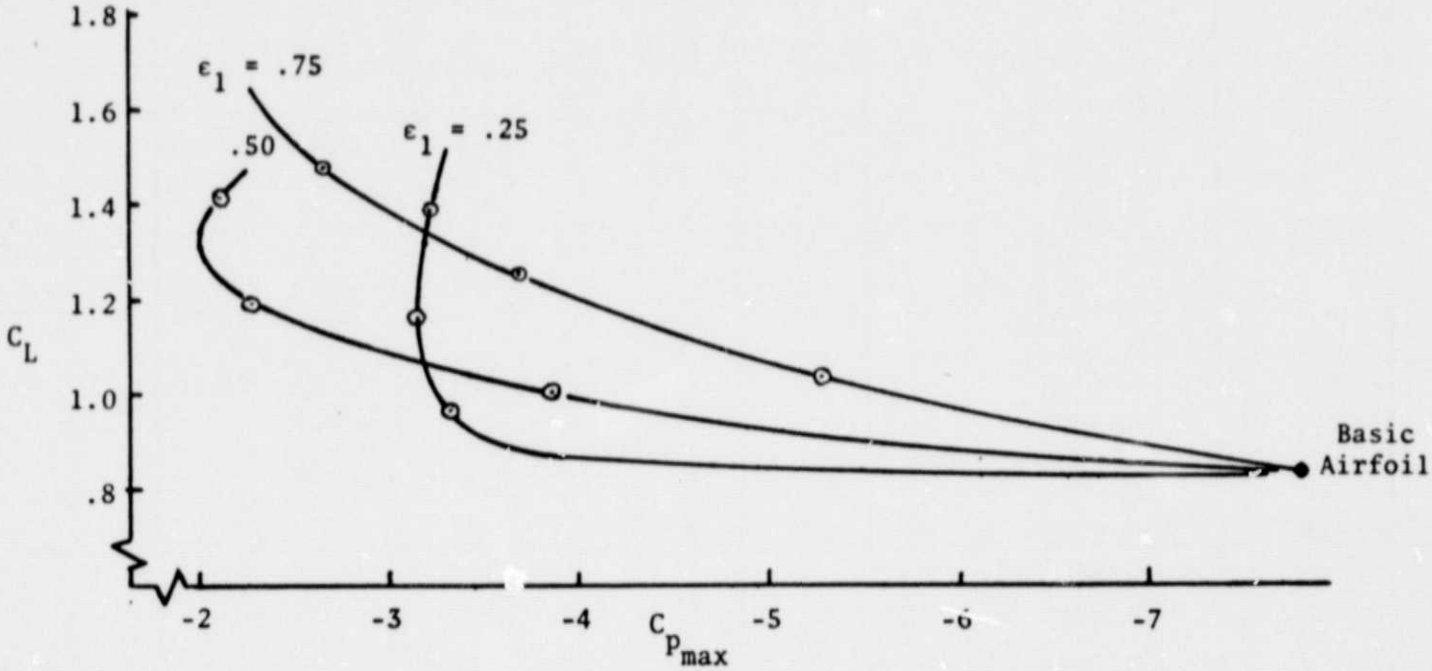


(a) 64-206 Airfoil

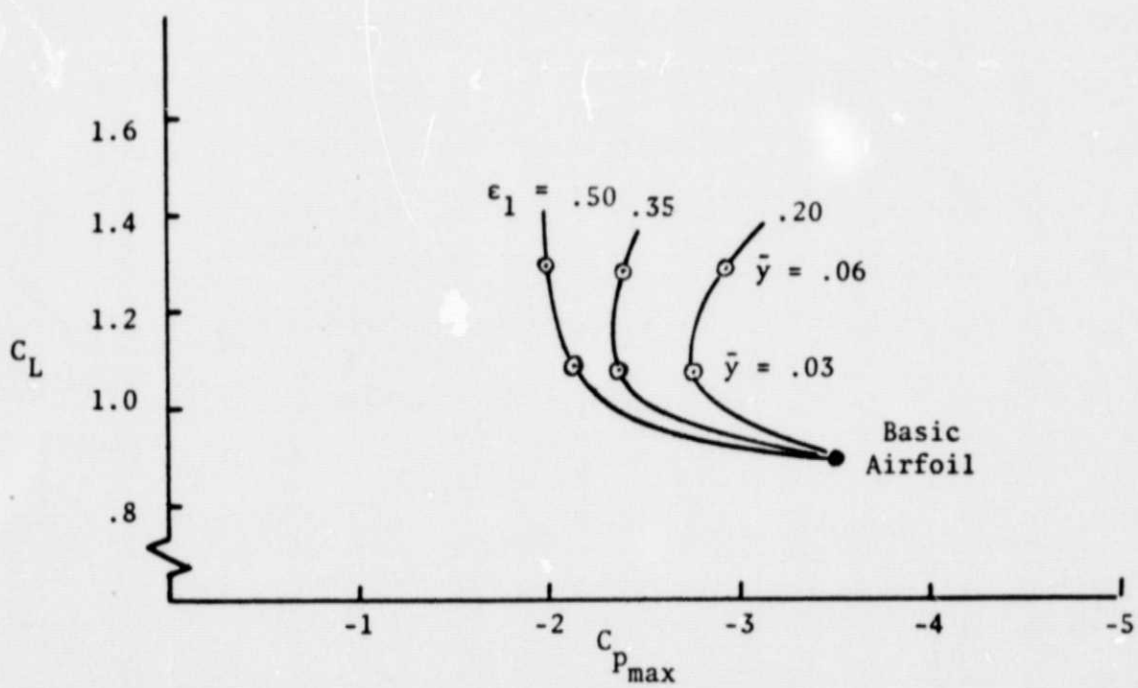


(b) 64_1-212 Airfoil

FIGURE 5. LIFT AND MOMENT VARIATIONS

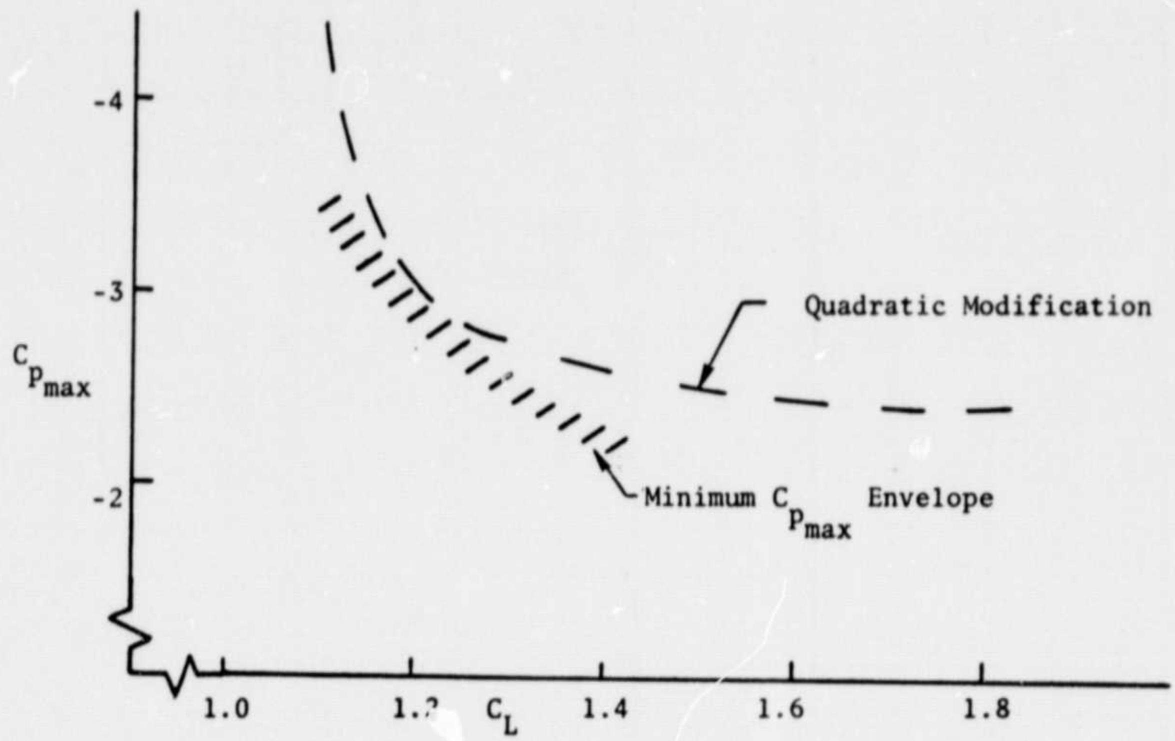


(a) 64-206 Airfoil

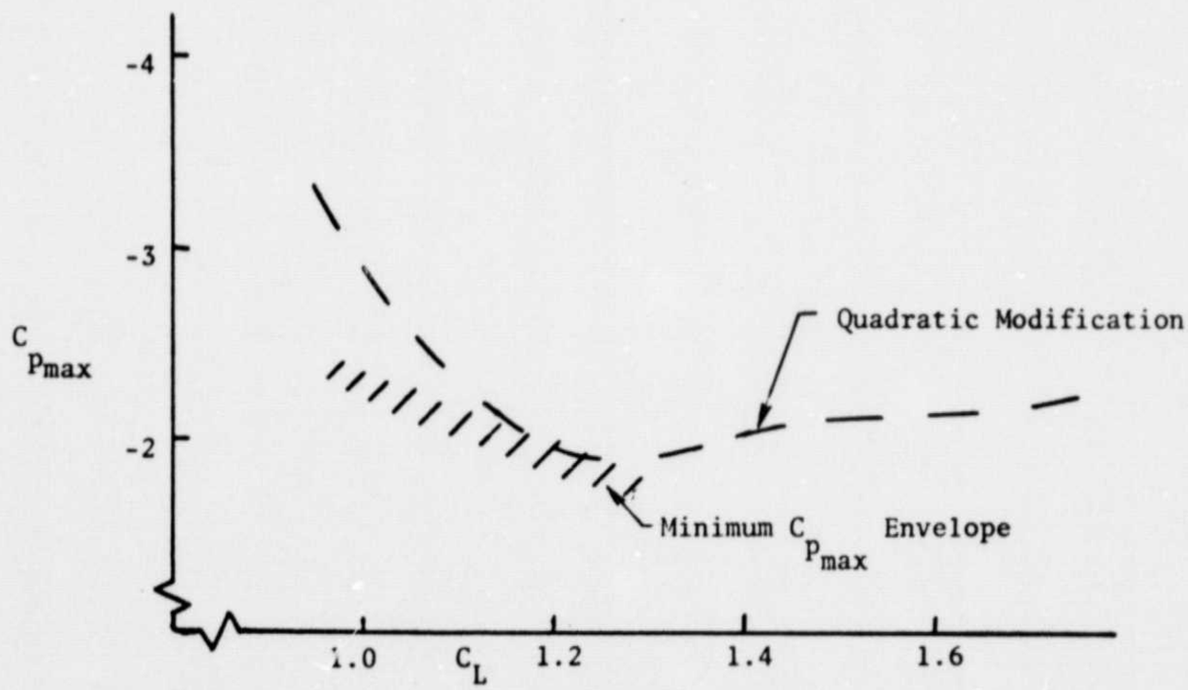


(b) 64_1-212 Airfoil

FIGURE 6. LIFT AND PEAK PRESSURE VARIATIONS



(a) 64-206 Airfoil



(b) 64_1-212 Airfoil

FIGURE 7. MINIMUM PEAK PRESSURE OBTAINABLE FOR GIVEN LIFT

APPENDIX A

CHORDWISE LOCATION OF MAXIMUM THICKNESS

The distribution function used in this study is

$$\Delta y(x) = Ax^{\varepsilon_1} (1 - x)^{\varepsilon_2} \tag{A-1}$$

and the variation of this function is smooth for $0 \leq x \leq 1$. The point of maximum additional thickness occurs when

$$\Delta y'(x) = \Delta y(x) \left[\varepsilon_1 x^{-1} - \varepsilon_2 (1 - x)^{-1} \right] = 0 \tag{A-2}$$

This shows that the chordwise location of the point of maximum thickness is

$$\bar{x} = \left[\frac{\varepsilon_1}{\varepsilon_1 + \varepsilon_2} \right] \tag{A-3}$$

and the value of the maximum thickness is then found in terms of the parameters as

$$\Delta y_{max} = \bar{y} = A \left[\frac{\varepsilon_1^{\varepsilon_1} \varepsilon_2^{\varepsilon_2}}{(\varepsilon_1 + \varepsilon_2)^{\varepsilon_1 + \varepsilon_2}} \right] \tag{A-4}$$

For the case studied in this report, $\varepsilon_2 = 1$, and the parameter A is

$$A = \bar{y} \left[\frac{(1 + \varepsilon_1)^{1 + \varepsilon_1}}{\varepsilon_1^{\varepsilon_1}} \right] \tag{A-5}$$

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